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Robust Evolutionary Approach to Mitigate Low Frequency Oscillation in a Multi-machine Environment

K. Mazlumi, M. Azari
Electrical Engineering Department, Faculty of Engineering, University of Zanjan, Iran
Email: kmazlumi@znu.ac.ir, m.azari@znu.ac.ir

Abstract— **This paper proposes a new optimization algorithm known as Modified Shuffled Frog Leaping Algorithm (MSFLA) for optimal designing of PSSs controller. The design problem of the proposed controller is formulated as an optimization problem and MSFLA is employed to search for optimal controller parameters. An eigenvalue based objective function reflecting the combination of damping factor and damping ratio is optimized for different operating conditions. The proposed approach is applied to optimal design of multi-machine power system stabilizers. Three different power systems, A Single Machine Infinite Bus (SMIB), four-machine of Kundur and ten-machine New England systems are considered. The obtained results are evaluated and compared with other results obtained by Genetic Algorithm (GA). Eigenvalue analysis and nonlinear system simulations assure the effectiveness and robustness of the proposed controller in providing good damping characteristic to system oscillations and enhancing the system dynamic stability under different operating conditions and disturbances.**

***Index Terms*— Multi-machine power system, Genetic Algorithm (GA), Modified Shuffled Frog Leaping Algorithm (MSFLA), PSS design, Damping oscillations**

I. Introduction

The extension of interconnected power systems is continually increasing because of the constantly growth in electric power demand. At the same time, the power systems are almost operated ever closer to their transient and dynamic stability limits. With heavy power transfers, such systems exhibit inter-area modes of oscillation of low frequency (0.1–0.8 Hz). The stability of these modes has become a source of preoccupation in today's power systems. In some cases, the related oscillatory instability may lead to major system blackouts [1]. Due to their flexibility, easy implementation and low cost, Power System Stabilizers (PSSs) stay the most used devices to damp small signal oscillations (0.1–2 Hz) and enhance power system dynamic stability [2]. PSS parameter setting is commonly based on the linearization of power system model around a nominal operating point. The purpose is to provide an optimal performance at this point as well as over a wide range of operating conditions and system configuration [3].

The past two decades have seen an explosion of metaheuristic optimization method. Numerous algorithms based on these methods have been widely applied to the problem of multi-machine PSS design. New approaches based on GAs to optimize the PSS parameters in multi-machine power systems are developed in [4]. A GA based-approach, taking several oscillation modes into consideration for avoiding suboptimal damping performance in other modes is used in [5]. In [6], three PSO algorithms based PSSs for an interconnected power system composed of three stand alone power systems is developed. A PSO based-indirect adaptive fuzzy PSS to damp inter-area modes of oscillation following disturbances in power systems is presented in [7]. In [8] a hybrid optimization technique is presented for optimum tuning of PSS parameters in a multi-machine power system. The hybrid technique is derived from PSO by adding the passive congregation model. A Modified PSO algorithm (MPSO) is proposed in [9] for optimal placement and tuning of PSSs in power systems. The MPSO integrated the PSO with passive congregation (to decrease the possibility of a failed attempt at detection or a meaningless search) and the chaotic sequence (to improve the global searching capability). A Bacteria Foraging Algorithm (BFA) based optimal neuro-fuzzy scheme is developed in [10] to design intelligent adaptive PSSs for improving the dynamic and transient stability performances of multi-machine power systems. In [11], an Artificial Bee Colony (ABC) algorithm is employed for better stability of the power system, while an ABC algorithm based rule generation method is proposed in [12] for automated fuzzy PSS design to improve power system stability and reduce the design effort. A new hybrid DE algorithm, called gradual self-tuning hybrid DE, is developed in [13] for rapid and efficient searching of an optimal set of PSS parameters. A DE algorithm is employed in [14] to tune multiband PSSs in a portion of the high voltage Mexican power grid.

In this paper, the problem of PSS design is formulated as a multi-objective optimization problem and MSFLA is used to solve this problem. The PSSs parameters designing problem is converted to an optimization problem with the multi-objective function including the desired damping factor and the desired damping ratio of the power system modes. The capability of the proposed MSFLA is tested on three power systems called Single Machine Infinite Bus (SMIB), four-machine of Kundur and ten-machine New England systems under different operating conditions in comparison with the GA [15] based tuned PSS (GAPSS) through some performance indices. Results reveal that the proposed method achieves stronger performance for damping low frequency oscillations as well as tuning controller under different operating conditions than other methods and is superior to them.

II. Design of Objective Function

For this purpose, a multi-objective function comprising the damping factor and the damping ratio is considered as follows [15]:

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$$J = \sum_{j=1}^{n_p} \sum_{\sigma_{i,j} \geq \sigma 0} [\sigma_0 - \sigma_{i,j}]^2 + a \sum_{j=1}^{n_p} \sum_{\xi_{i,j} \leq \xi_0} [\xi_0 - \xi_{i,j}]^2 \quad (1)$$

This method's performance is shown in Fig. 1.

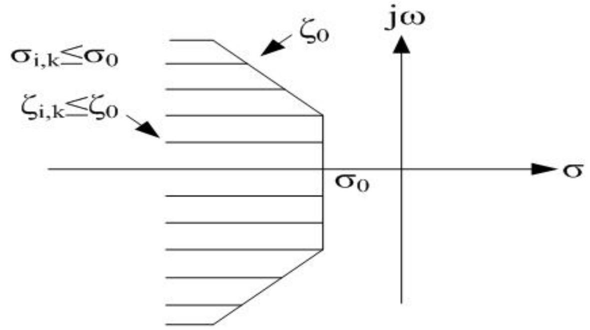

Figure 1. Objective performance.

Different inequalities have been proposed to be satisfied [8]:

1) $\xi_k \geq \xi_{madr}$. $k = (1,2,...n - gen - 1)$

2) $(1-\gamma_{\min})\omega_k \leq \omega_k + \mathrm{Im}(\Delta\lambda_k) \leq (1+\gamma_{\max})\omega_k$

Where γ is defined according to system specifications.

3) $\xi_i \geq \xi_{mmdr}$. The performance of this technique has been shown in Fig. 2.

In order to use advantages of the above mentioned references, objectives are considered as follow:

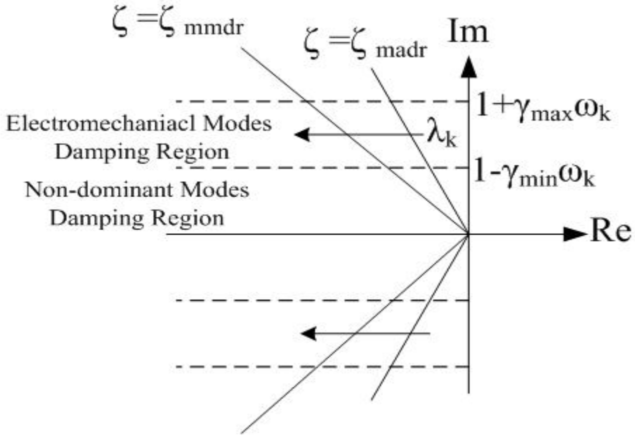

Figure 2. Objective's performance.

$$Minimize: y_1 = (Min(abs(\sigma_k))) \quad (2)$$

$$Minimize \ : y_2 = (Min\ (\xi_k)) \quad (3)$$

Subject to:

1) $\sigma_i < 0$, for all eigenvalues. This condition guarantees system small signal stability.

2) For the electro-mechanical modes: $a \leq \omega_k \leq b$

3) For all other modes: $\xi_i \geq \xi_{mmdr}$

The value of ξ_{mmdr} for different systems is shown in Table I.

TABLE I. THE VALUE OF ξ_{mmdr} FOR DIFFERENT SYSTEMS

Parameters	SMIB	TAFM	New England
ζ_{mmdr}	0.2	0.2	0.1

For the CPSS, the vector of parameters ids defined as follow:

$$x = (T_1, T_2, T_3, T_4, V_{S\max}, k_{PSS}) \quad (4)$$

The CPSS parameters bounds are shown in Table II.

TABLE II. THE CPSS PARAMETERS BOUNDARIES

Parameters	T_1	T_2	T_3	T_4	V_{Smax}	K_{PSS}
Maximum	1	1	10	10	0.5	100
Minimum	0.01	0.01	0.01	0.01	0.05	10

The main object here is to minimize the following objective function:

$$OF = (r_1 \times y_1 + r_2 \times y_2)^{-1} \quad (5)$$

Where y_1 and y_2 are objective functions. In order to have comprehensive investigation, different values for weights, r_1 and r_2 are assumed.

III. MODIFIED SHUFFLED FROG LEAPING ALGORITHM

In the natural memetic evolution of a frog population, the ideas of the worse frogs are influenced by the ideas of the better frogs, and the worse frogs tend to jump toward the better ones for the possibility of having more foods. The frog leaping rule in the shuffled frog leaping algorithm (SFLA) is inspired from this social imitation, but it performs only the jump of the worst frog toward the best one [15]. According to the original frog leaping rule presented above, the possible new position of the worst frog is restricted in the line segment between its current position and the best frog's position, and the worst frog will never jump over the best one (Fig. 3). Clearly, this frog leaping rule limits the local search space in each memetic evolution step.

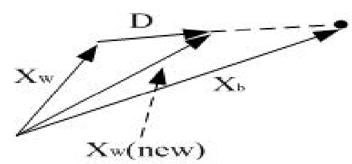

Figure 3. The original frog leaping rule.

This limitation might not only slow down the convergence speed, but also cause premature convergence. In nature, because of imperfect perception, the worst frog cannot locate exactly the best frog's position, and because of inexact action, the worst frog cannot jump right to its target position. Considering these uncertainties, we argue that the worst frog's new position is not necessary restricted in the line connecting its current position and the best frog's position. Furthermore, the worst frog could jump over the best one. This idea leads to a new frog leaping rule that extends the local search space as illustrated in Fig. 4 (for 2-dimensional problems). The new frog leaping rule is expressed as:

$$D = r.c(X_b - X_w) + W \quad (6)$$

$$W = [r_1 w_{1,\max}, r_2 w_{2\max}, \ldots, r_s w_{s,\max}]^T \quad (7)$$

$$X_w(new) = \begin{cases} X_w + D & if \|D\| \leq D_{\max} \\ X_w + \dfrac{D}{\sqrt{D^T D}} D_{\max} & if \|D\| > D_{\max} \end{cases} \quad (8)$$

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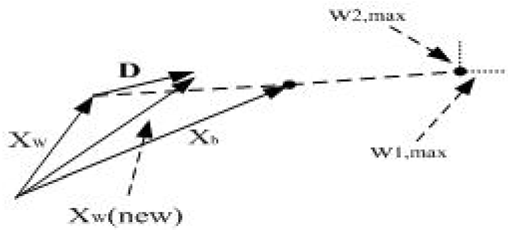

Figure 4. The new frog leaping rule.

where r is a random number between 0 and 1; c is a constant chosen in the range between 1 and 2; r_i (1<i<S) are random numbers between -1 and 1; $w_{i,max}$ (1<i<S) are the maximum allowed perception and action uncertainties in the i_{th} dimension of the search space; and D_{max} is the maximum allowed distance of one jump. The flow chart of the local memetic evolution using the proposed frog leaping rule is illustrated in Fig. 5.

The new frog leaping rule extends the local search space in each memetic evolution step; as a result it might improve the algorithm in term of convergence rate and solution performance provided that the vector $W_{max}=[w_{1,max},\ldots, w_{S,max}]^T$ is appropriately chosen. However, if $\|W_{max}\|$ is too large, the frog leaping rule will loss its directional characteristic, and the algorithm will becomes more or less random search. Therefore, choosing a proper maximum uncertainty vector is an issue to be considered for each particular optimization problem.

IV. Case Study

A. Single Machine Infinite Bus (SMIB) System

In order to evaluate the proposed method, a single machine infinite bus (SMIB) model of a power system is assumed initially. In this model, a typical 500MVA, 13.8 kV, 50Hz synchronous generator is connected to an infinite bus through a 500MVA, 13.8/400KV transformer and 400KV, 350 Km transmission line [15]. This system has been shown in Fig. 6.

Figure 6. Single Machine

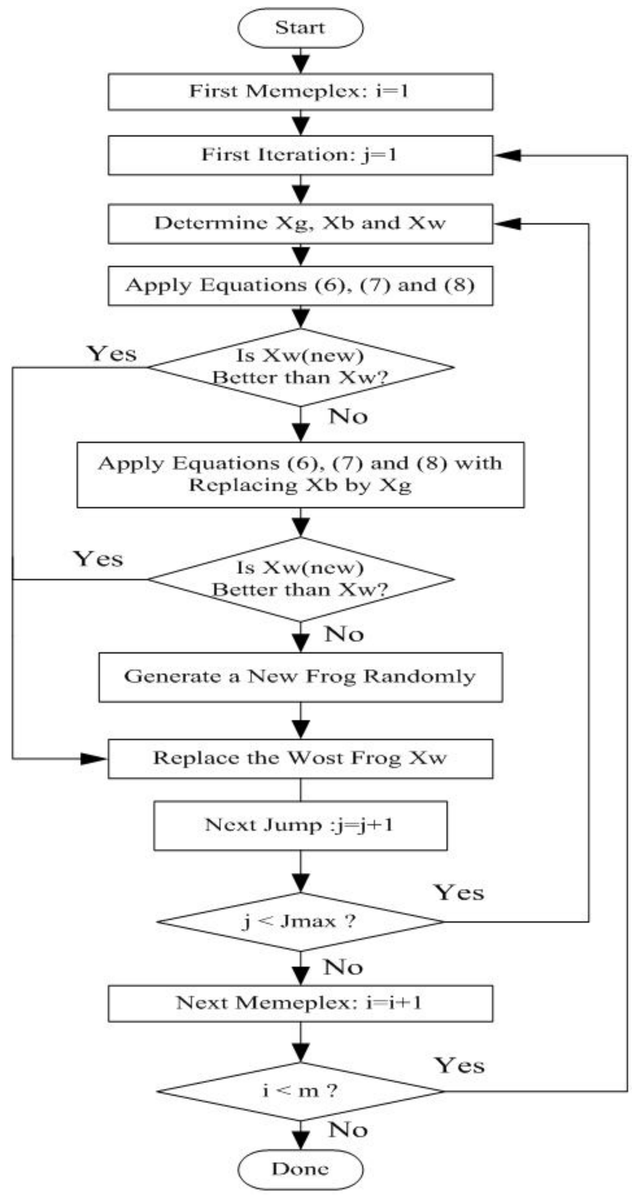

Figure 5. The MSFLA flowchart.

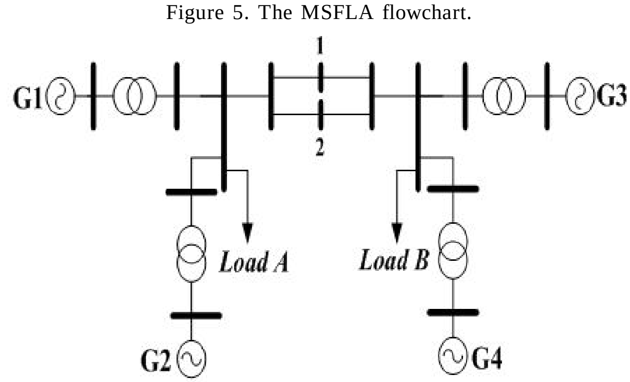

Figure 7. Four-Machine (TAFM) system.

D. PSS Structure

The model of the CPSS is illustrated in Fig. 9. This model consists of two phase-lead compensation blocks, a gain block and a signal washout block. The value of T_W is usually not critical and it can range from 0.5 to 20 s. In this paper, it is

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fixed to 10 s. the six other constant coefficients of the model (T_1 , T_2 , T_3 , T_4 , V_{Smax} and K_{PSS}) should be designed properly.

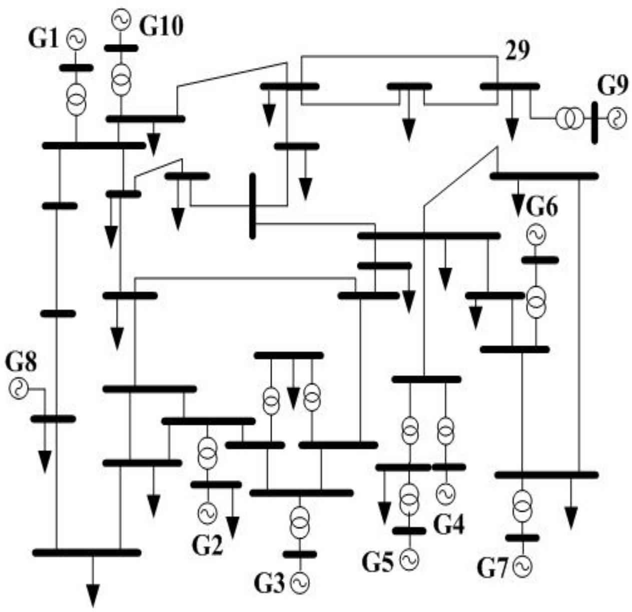

Figure 8. New England power system.

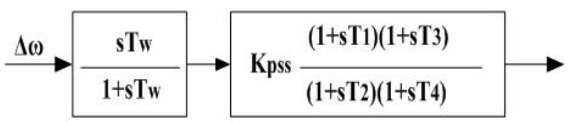

Figure 9. Power system stabilizer.

V. Simulation Result

The proposed MSFLA methodology and GA are programmed in MATLAB running on an Intel w Core TM2 Duo Processor T5300 (1.73 GHz) PC with 1 GB RAM. It is applied on ***SIMB***, TAFM and New England ***systems*** to demonstrate its abilities. The effect of MSFLA parameters on average fitness function (among 100 trials) is investigated. The colony size (N_C) tried was 100. Hundred independent trials have been made with 100 iterations per trial. The performance of the MSFLA also depends on the number of colonies. The parameters of MSFLA are selected based on the average fitness function. After a number of careful experimentation, following optimum values of MSFLA parameters have finally been settled: NC = 100; D_{max} = 0.7, r_i= 1; C=1.3; r=0.6.

A. SMIB System

At first the design process is applied to design a PSS for a SMIB system. The minimum fitness value evaluating process is shown in Fig. 10.

Table III. Optimal PSS Parameters Using MSFLA and GA Schemes for SMIB System

Method	T_1	T_2	T_3	T_4	V_{Smax}	K_{PSS}
GA	0.8	0.5	1.3	6.4	0.34	33.2
MSFLA	0.6	0.1	1	7	0.3	21.4

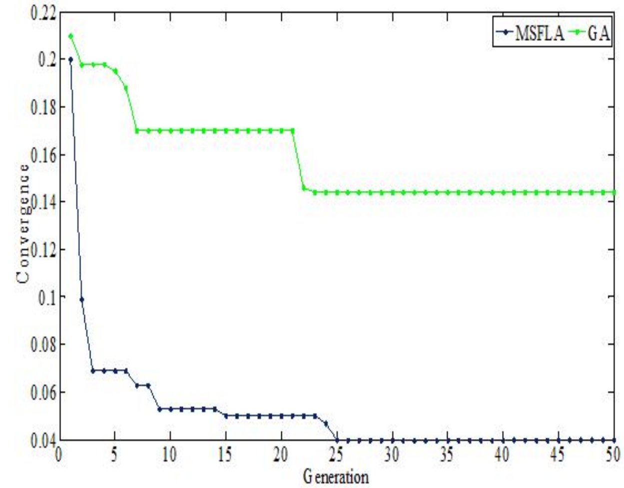

Figure 10. Variations of objective function for SMIB system.

The MSFLA algorithm is run several times and then optimal set of PSS parameters is selected. The set value of PSSs' parameters using both the proposed MSFLA and GA are given in Table III.

To have a better understanding, dominant oscillatory poles' maps of the system, comprising some optimum PSSs are shown in Fig. 11. As it obvious from the figure, the open-loop system is unstable.

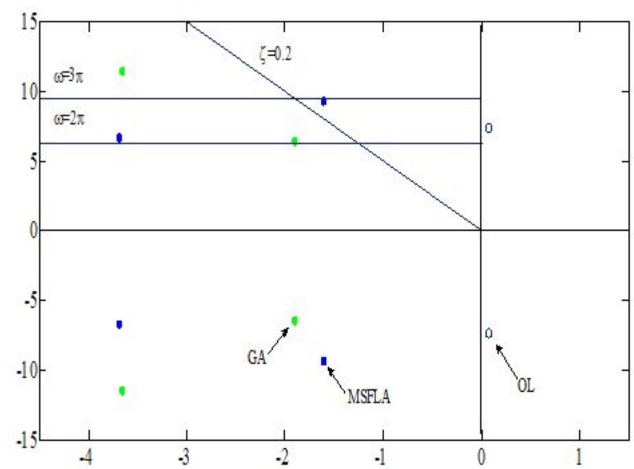

Figure 11. Dominant modes of SMIB system.

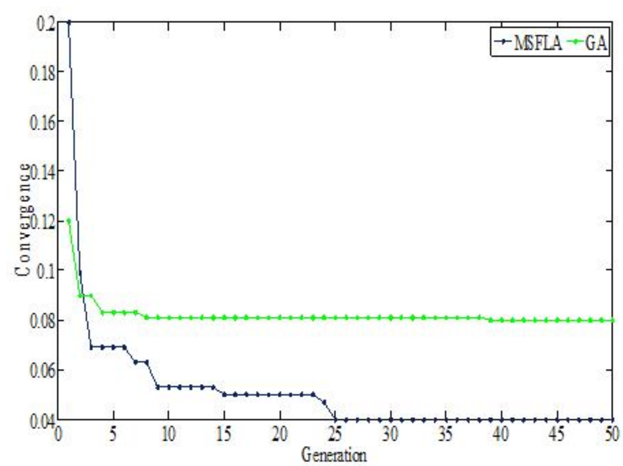

Figure 12. Variations of objective function for TAFM system.

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B. TAFM System

The other system employed to evaluate the proposed method is the Four-Machine (TAFM) (Fig. 7). Two PSSs with similar settings are installed at G_1 and G_4. Fig. 12 shows the minimum fitness value evaluating process.

To have a better understanding, dominant oscillatory poles' maps of the system, comprising some optimum PSSs are shown in Fig. 13. It can be understand from the figure that the electro-mechanical modes are close together, but there is a higher difference in the other oscillatory mode of some PSSs. In addition, instability of the open-loop system is clear. The designed PSSs' characteristics are presented in Table IV.

C. New England System

One of most important issues in PSS design process is to test proposed method in a large system. Hence, in order to reveal its robust performance, the proposed technique, is applied to New England system.

The convergence value of MSFLA and GA is presented in Fig. 14, introducing acceptable improvement through

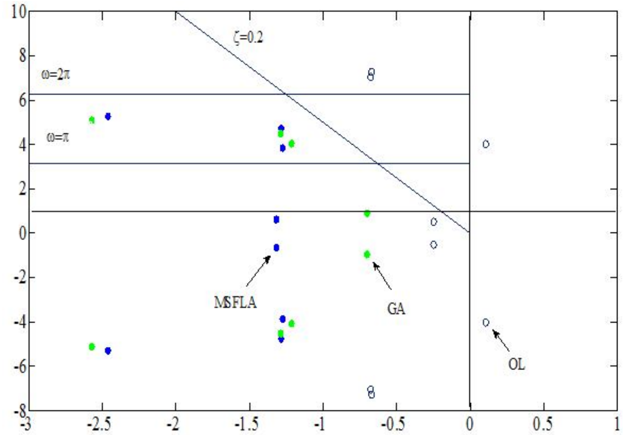

Figure 13. Dominant modes of TAFM system.

generation increment. The system's dominant oscillatory poles' map with candidate MSFLA and GA based PSSs is drawn in Fig. 15. The parameters' numerical values of both algorithms are given in Table V. The comparative evaluation from test results shows its robust performance.

TABLE IV. OPTIMAL PSS PARAMETERS USING MSFLA AND GA SCHEMES FOR TAFM SYSTEM

Method	GA						MSFLA					
	T_1	T_2	T_3	T_4	V_{Smax}	K_{PSS}	T_1	T_2	T_3	T_4	V_{Smax}	K_{PSS}
G1	0.36	0.04	1.6	7.1	0.3	68	0.73	0.11	1.78	6.7	0. 2	36.8
G4	0.84	0.3	2.3	8.3	0.28	12.9	1	0.06	3	5	0.03	45

TABLE V. OPTIMAL PSS PARAMETERS USING MSFLA AND GA SCHEMES FOR NEW ENGLAND SYSTEM

Method	GA						MSFLA					
	T_1	T_2	T_3	T_4	V_{Smax}	K_{PSS}	T_1	T_2	T_3	T_4	V_{Smax}	K_{PSS}
G1	0.08	0.1	0.47	0.05	0.2	57.6	0.1	0.2	1. 8	0.11	0. 25	42
G2	0.07	0.9	1.12	0.05	0.3	27.8	1.2	0.1	0.3	0.05	0. 33	27.3
G3	0.09	0.33	0.14	0.045	0.25	75	0.09	0. 45	1.1	1.4	0.36	13
G4	0.06	0.1	0.33	1	0.3	30.3	0.05	0.06	1.73	1	0.2	8
G5	0.08	0.08	1.17	1.8	0.2	80	0.09	0.09	0.67	1.87	0.19	99
G6	0.09	0.1	0.5	0.06	0.28	47.7	0.1	0.2	1.68	0.075	0.24	83
G7	0.1	0.15	0.47	1.6	0.35	10.5	0.06	0.08	1	2	0.32	11
G8	0.08	0.09	0.75	1.67	0.28	67.6	0.1	0.03	0.06	2.4	0.2	37
G9	0.04	0.11	0.8	0.04	0.21	22.9	0.02	0.31	0.5	0.33	0.28	36.8

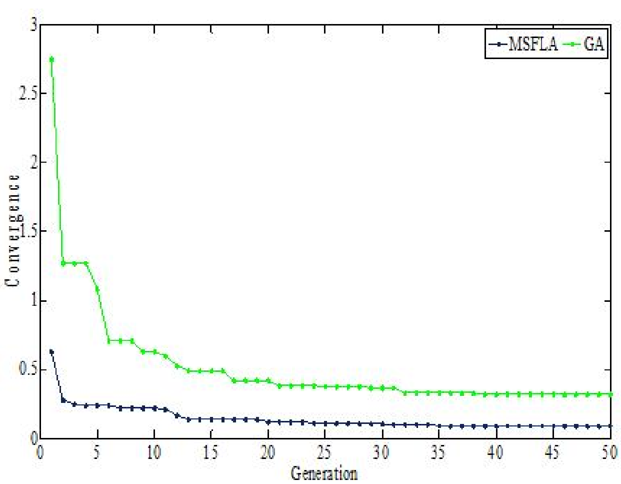

Figure 14. Variations of objective function for New England system.

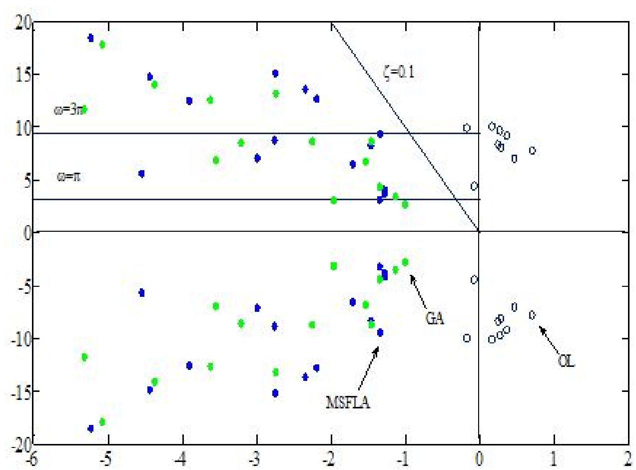

Figure 15. Dominant modes of New England system.

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A comparison among the results of the proposed algorithm MSFLA and GA presents in Table VI. Comparison the proposed optimization algorithm (MSFLA) with those of the other methods confirms the effectiveness of the proposed method. Table 5 provides the average value (AFF) of the objective function, based on the proposed method and the other one. This would show the convergence characteristics of the proposed MSFLA compared with other method. The average value of objective function in the proposed MSFLA method is less than GA. This means that the MSFLA is more robust compared to GA. Execution time (MT) complexity of each optimization method is very important for its application to real systems. The execution time of the proposed MSFLA compared with other methods is given in the last row of Table VI. One of the main advantages of the proposed method is that the convergence of MSFLA algorithm is faster and less time consuming (see Table VI) as compared to the other applied methods. Because the proposed algorithm (MSFLA) provides the correct answers with high accuracy in the initial iterations which make the responding time of this algorithm extremely low.

TABLE VI. COMPUTATIONAL PERFORMANCE COMPARISON BETWEEN MSFLA AND GA

System	GA		MSFLA	
	AFF	MT(Sec)	AFF	MT(Sec)
SMIB	0.056	4854	0.0514	3647
TAFM	0.094	12216	0.08	10816
New England	0.4263	31943	0.2126	27214

D. Nonlinear Time Domain Simulation

In order to evaluate the performance of the MSFLA based tuned PSSs under fault conditions, some large disturbances have been applied to the systems. Descriptions of three different faults applied to evaluate the robustness of PSSs are represented in Table VII.

TABLE VII. DISTURBANCES APPLIED TO THE SYSTEMS

System	Description
SMIB	6-cycle three phase ground fault at power plant bus cleared without equipment
TAFM	9-cycle three phase ground fault at bus 1 cleared without equipment
New England	6-cycle three phase ground fault at bus 29 cleared without equipment

Rotor speed deviation of a generator located close to the fault position and variations of active power of a selected line are plotted against time for various PSSs and the faulty operating condition as shown in Figs. 16 - 18.

As seen from Figures, the MSFLA based tuned PSSs achieves good robust performance and provides superior damping in comparison with the other methods. It can be concluded that the proposed MSFLA based PSSs controller provides much proper control signals than the GAPSSs and CPSSs.

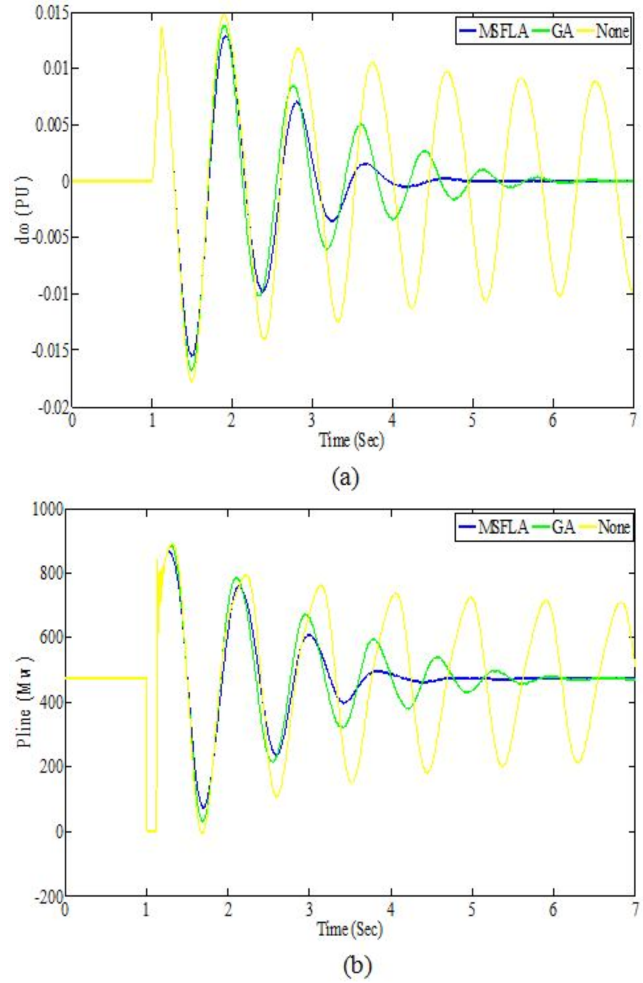

Figure 16. SMIB: a- Rotor speed deviation; b- Active power.

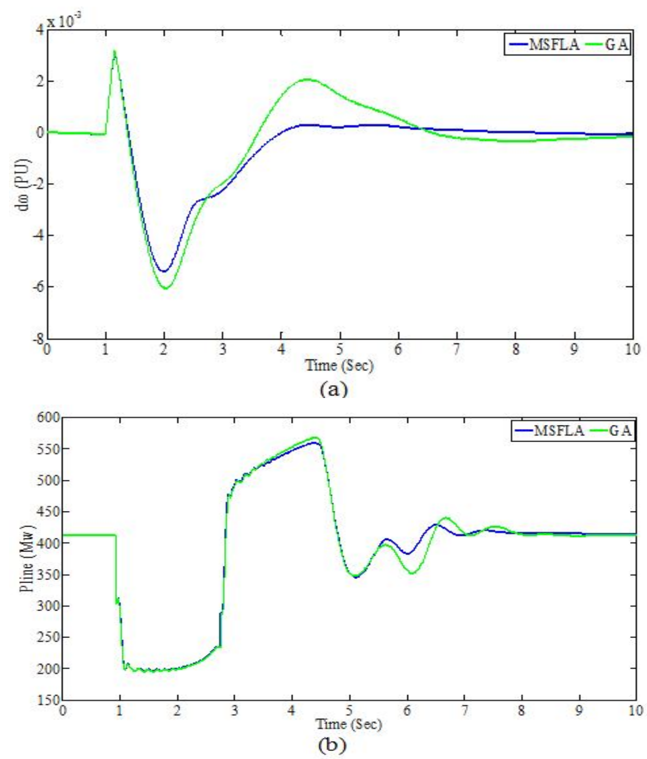

Figure 17. TAFM: a- Rotor speed deviation; b- Active power

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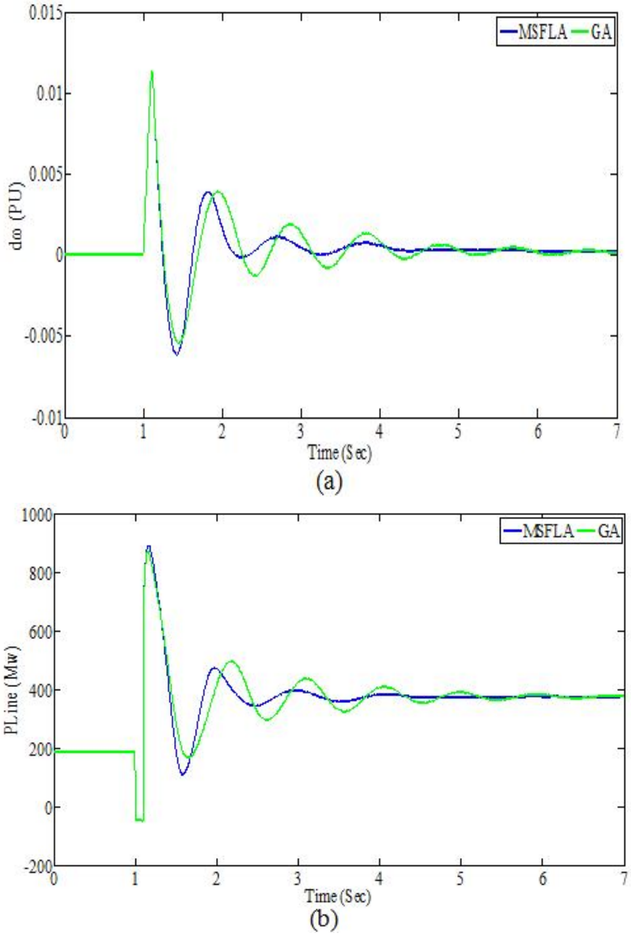

Figure 18. New England: a- Rotor speed deviation; b- Active power.

VI. Conclusions

In this paper a modified shuffled frog algorithm is proposed to tune the PSS parameters. The design strategy includes enough flexibility to set the desired level of the stability and performance, and to assume the practical constraints by introducing appropriate uncertainties. The approach effectiveness is validated on multi-machine PSS design for enhancing power system stability. The performance of MSFLA-PSSs design is compared to the results obtained with GA-based PSS design. It is revealed the optimization based on MSFLA can acquire better solutions as well as better convergence rate. In connection with power system stability, eigenvalue analysis is verified the effectiveness of the proposed scheme to provide good damping characteristics to electromechanical modes of oscillations. Nonlinear time-domain simulations are also demonstrated the robustness of the system with quick decay of system oscillations. Hence, the system dynamic stability can be well enhanced as well as the extension of the power transfer capability.

Appendix

n_p	The number of operating points
$\sigma_{i,j}$	The real part of the ith eigenvalue of the jth operating point
$\xi_{i,j}$	The damping ratio of the ith eigenvalue of the jth operating point
ξ_{madr}	The minimum acceptable damping ratio
ω_k	The frequency of kth mode
ξ_{mmdr}	The minimum marginal damping ratio
σ_k	The real part of the kth electromechanical modes
ξ_k	The damping ratio of the kth electromechanical modes
a	The empirically considered limits of frequency
b	The empirically considered limits of frequency
OF	Objective function

References

[1] B. Pal and B. Chaudhuri, Robust control in power systems, New York: Springer; 2005.

[2] P. Kundur, Power System Stability and Control, New York: McGraw-Hill, 1994.

[3] H. Alkhatib and J. Duveau, “Dynamic genetic algorithms for robust design of multi-machine power system stabilizers,” Int. J. Elect. Power Energy Syst, vol. 45, pp. 242–251, 2013.

[4] M.O. Hassan, S. J. Cheng and Z.A. Zakaria, “Optimization of conventional power system stabilizer to improve dynamic stability,” In: Proc. of the 5th IEEE Int. conf. on industrial electronics and applications (ICIEA), pp. 599–604, 2010.

[5] H.J. Wang, J. Min, J. Ma J, H.Y. Wang, H. J. Fu and Y. Y. Hu, “A study on PSS parameters optimizing for multiple low frequency oscillation modes,” In: Proc. of the IEEE Asia-Paciûc power and energy, Engineering conference (APPEEC)., pp. 1–4, 2011.

[6] H. E. Mostafa, M. A. El-Sharkawy, A. A. Emary and K. Yassin, “Design and allocation of power system stabilizers using the particle swarm optimization technique for an interconnected power system,” Electr Power Energy Syst, vol. 34, no. 1, pp. 57–65, 2012.

[7] T. Hussein, M. S. Saad, A. L .Elshafei and A. Bahgat, “Damping inter-area modes of oscillation using an adaptive fuzzy power system stabilizer,” Electr Power Syst Res, vol. 80, no. 12, pp. 1428–36, 2010.

[8] M. Eslami, H. Shareef, A. Mohamed and M. Khajehzadeh, “A hybrid PSO technique for damping ectro mechanical oscillations in large power system,” In: Proc. of the IEEE student conference on research and, development (SCOReD), p. 442–47, 2010.

[9] M. Eslami, H. Shareef, A. Mohamed and M. Khajehzadeh, “An efficient particle swarm optimization technique with chaotic sequence for optimal tuning and placement of PSS in power systems,” Electr Power Energy Syst, vol. 43, no. 1, pp. 1467–78, 2012.

[10] M. M. Beno, N. A. Singh, M.C. Therase and M. M. S. Ibrahim, “Design of PSS for damping low frequency oscillations using bacteria foraging tuned non-linear neuro-fuzzy controller,” In: Proc. of the 2011 IEEE GCC conference and exhibition (GCC),pp. 653–56, 2011.

[11] V. Ravi and K. Duraiswamy, “Effective optimization technique for power system stabilization using Artiûcial Bee Colony,” In: Proc. of 2012 IEEE Int. conf. on computer communication and informatics (ICCCI), pp. 1–6, 2011.

[12] O. Abedinia,B. Wyns and A. Ghasemi, “ Robust fuzzy PSS design using ABC,” In: Proc. Of the 10th IEEE Int. conf. on environment and, electrical engineering (EEEIC), pp. 1–4, 2011.

[13] S. K. Wang, “A novel objective function and algorithm for optimal PSS parameter design in a multi-machine power

DOI: 01.IJEPE.4.3.7

ACEEE Int. J. on Electrical and Power Engineering , Vol. 4, No. 3, November 2013

system," IEEE Trans Power Syst, vol. 99, no. 1, 2010.
[14] J. M. Ramirez, R.E. Correa and D. C. Hernández, "A strategy to simultaneously tune power system stabilizers," Electr Power Energy Syst, vol. 43, no. 1, pp. 818–29, 2012.
[15] S. Jalilzadeh and M. Azari, "Robust Tuning of the PSS Controller to Enhance Power System Stability," In: Proc. of 2012 Int. conf. on Advances in Computer and Electrical Engineering (ICACEE), Nov. 17-18, Manila (Philippines), pp. 8–12, 2012.

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